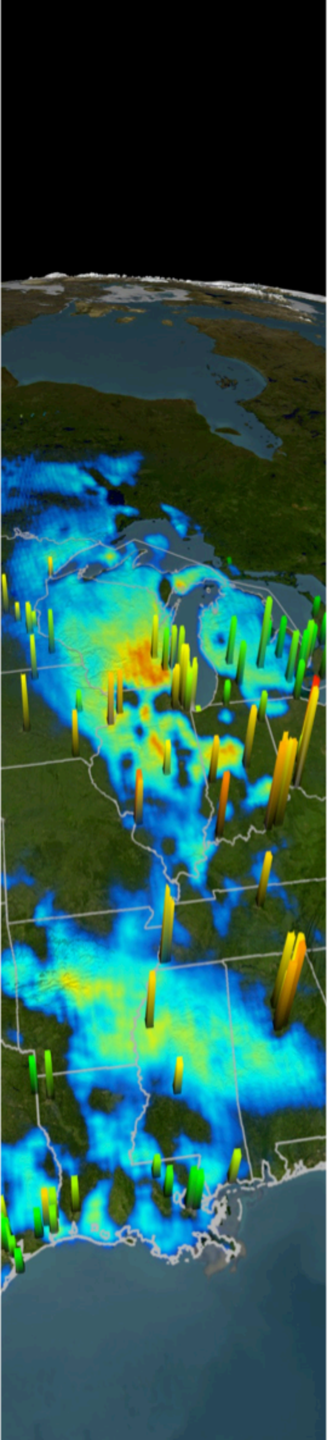

National Aeronautics and
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ARSET

Applied Remote Sensing Training

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Theoretical Basis for Converting Satellite Observations to Ground-Level PM2.5 Concentrations

Pawan Gupta, Melanie Follette-Cook

Monday, November 14, 2016

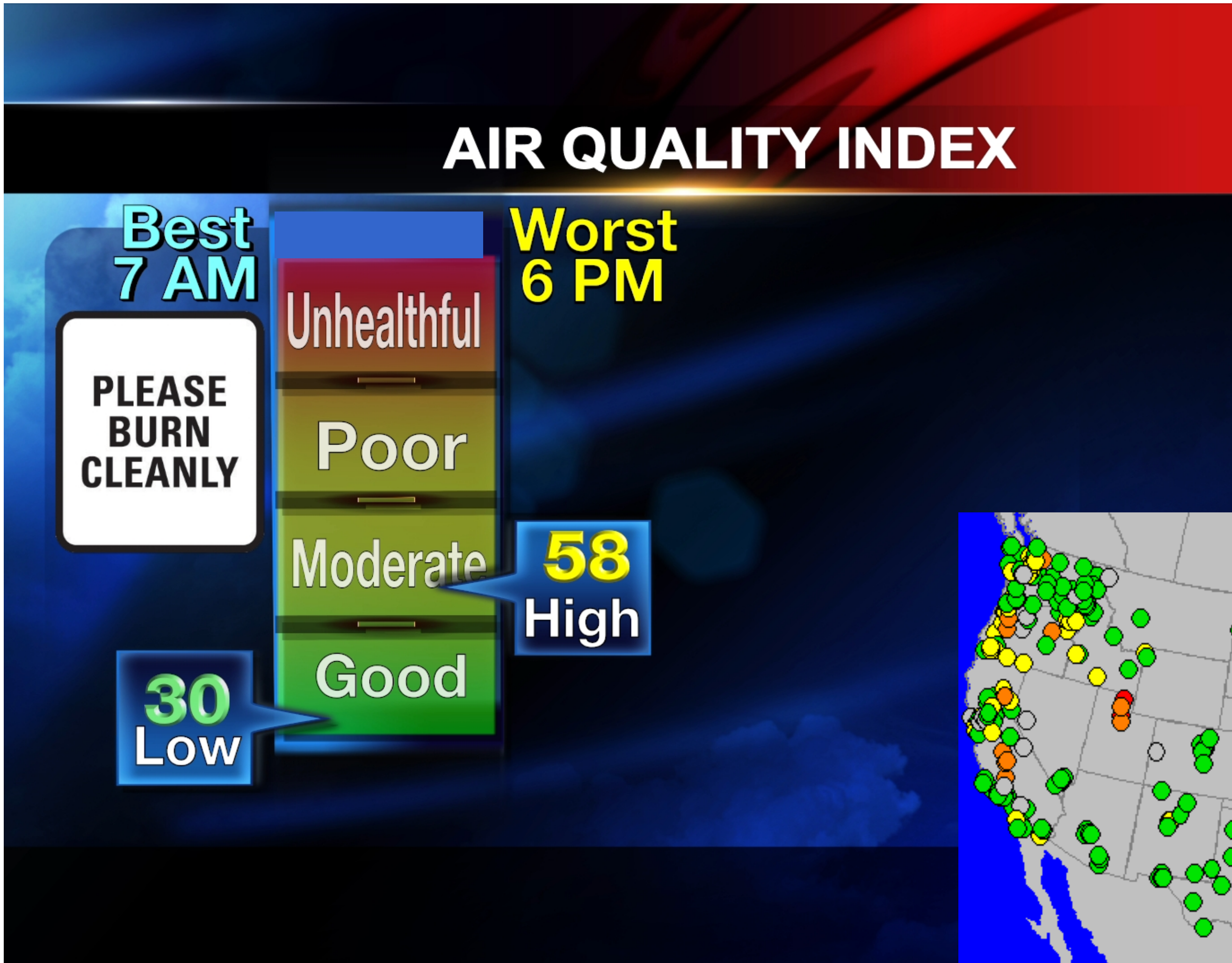
2nd International Smoke Symposium

Long Beach, CA, USA

Objectives

- Learn how to estimate PM2.5 mass concentration at surface level ($\mu g m^{-3}$) while using satellite derived Aerosol Optical Depth (AOD) at visible wavelengths

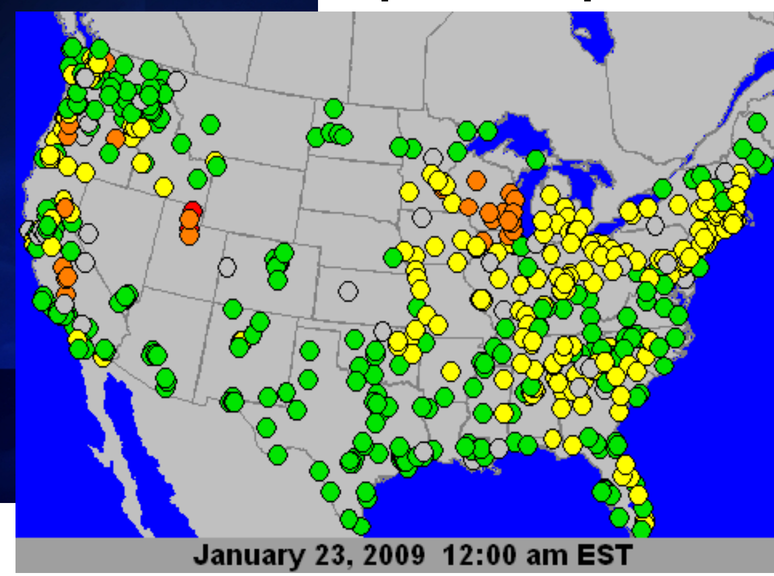
What are we looking for? And why?



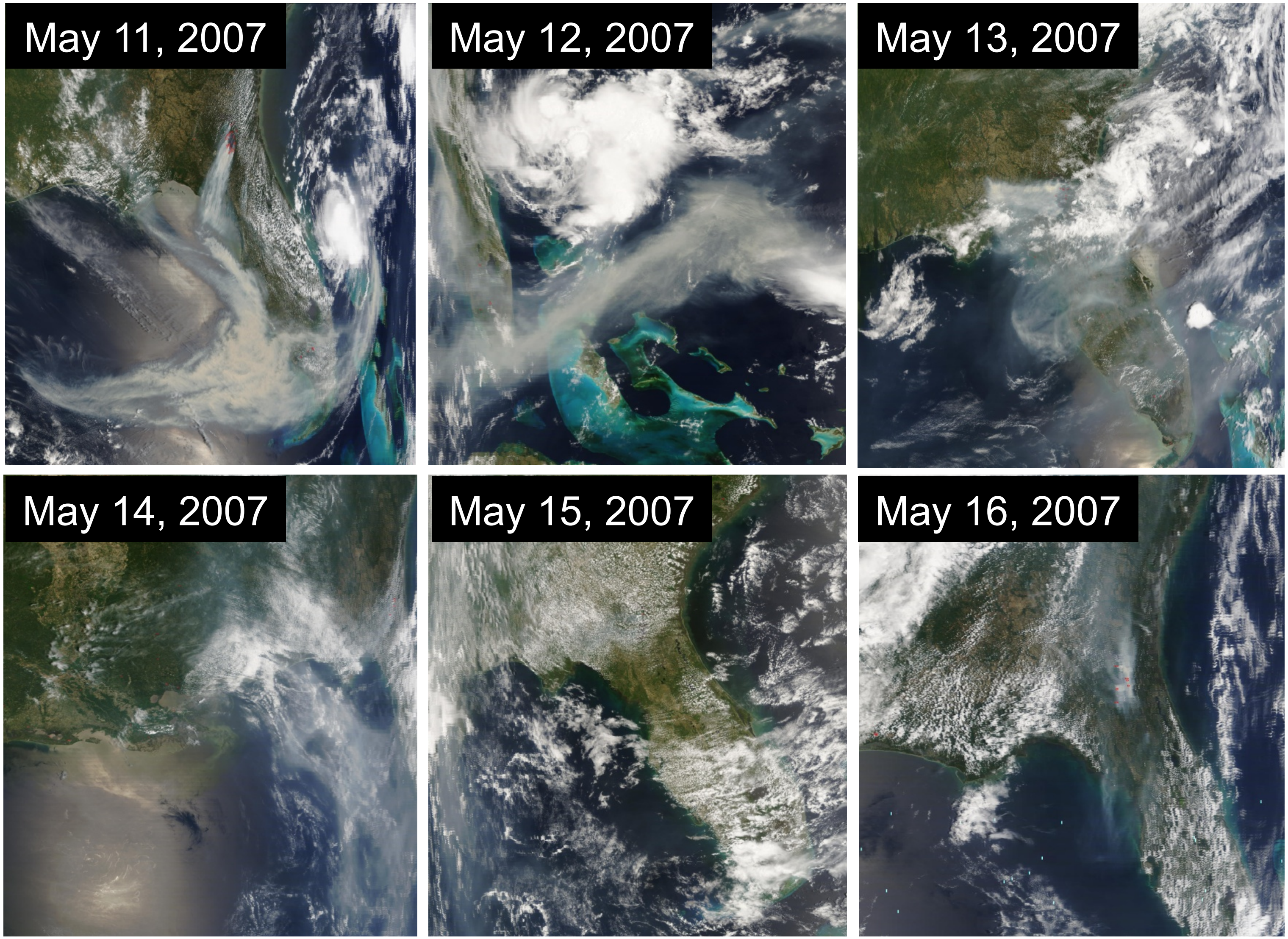
AIR QUALITY INDEX

Air Quality Index (AQI) Values	Levels of Health Concern
0 to 50	Good
51-100	Moderate
101-150	Unhealthy for Sensitive Groups
151-200	Unhealthy
201-300	Very Unhealthy
301 to 500	Hazardous

Spatial Gaps

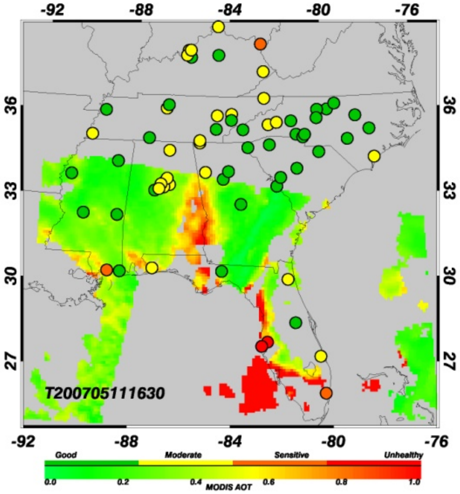


MODIS-Terra True Color Images

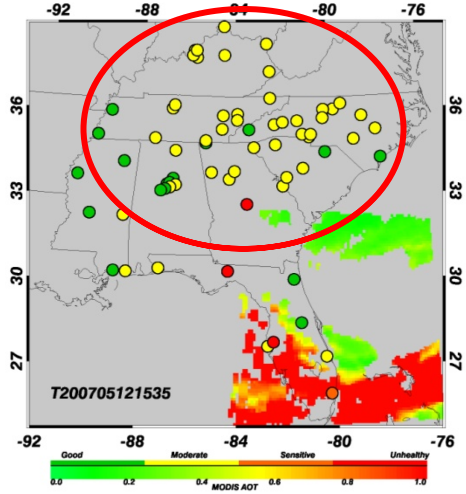


MODIS-Terra Aerosol Optical Thickness

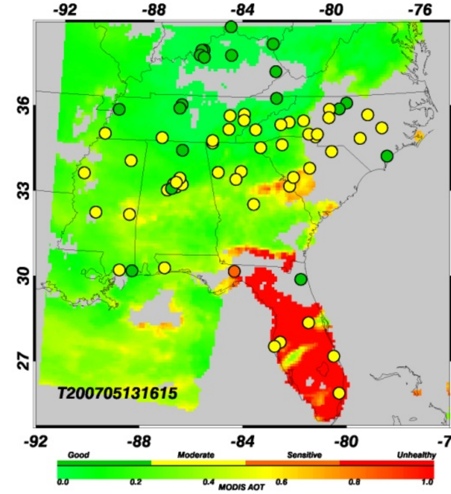
May 11, 2007



May 12, 2007



May 13, 2007



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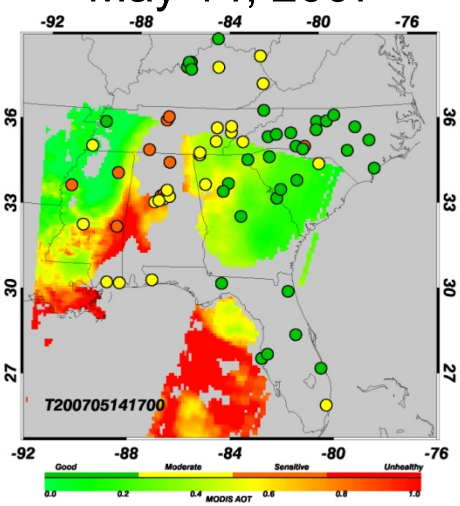

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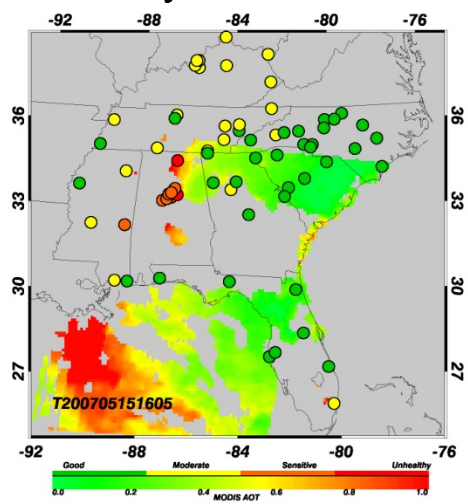
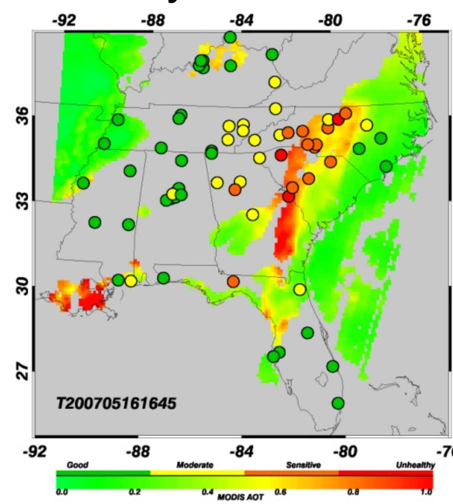
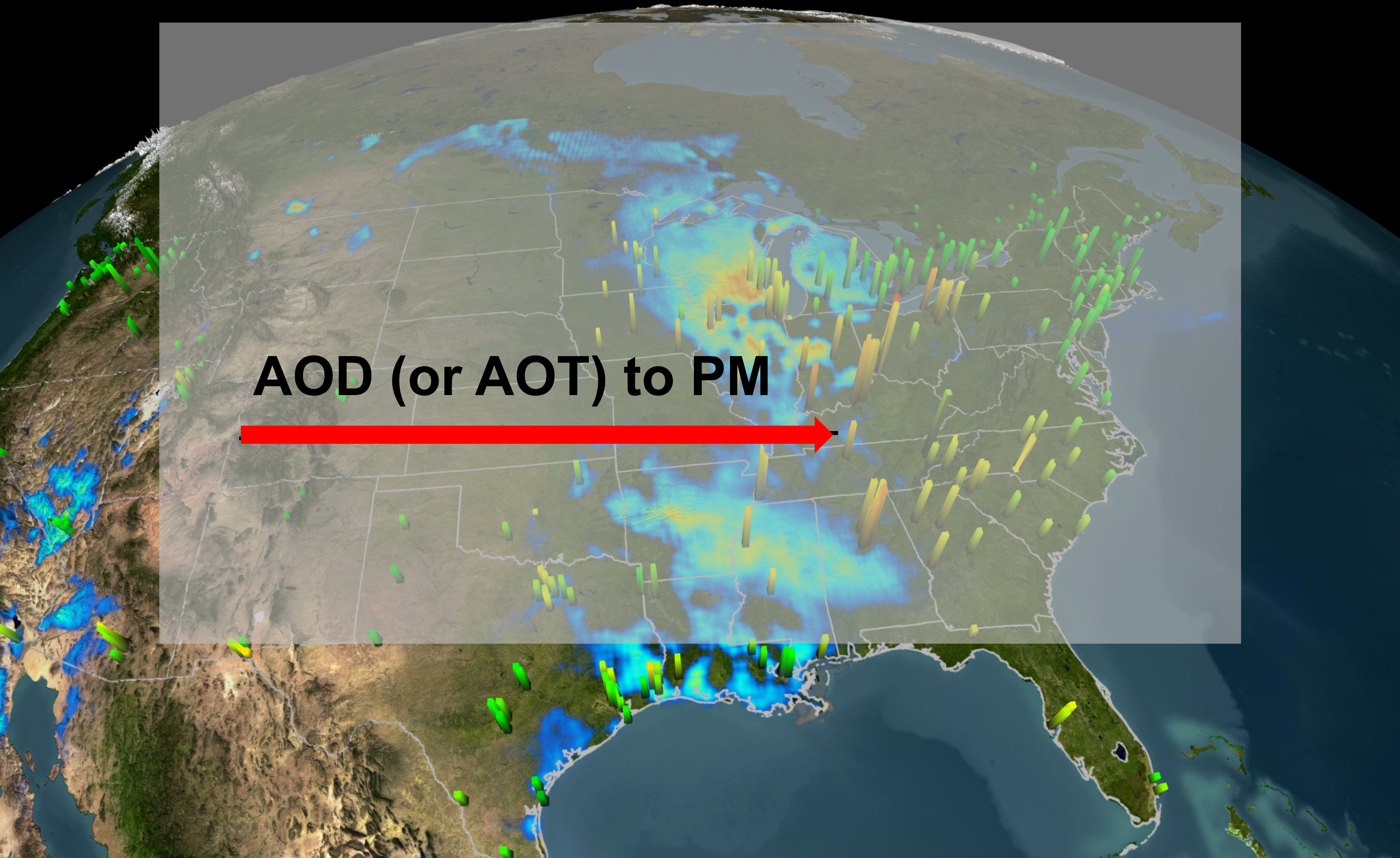
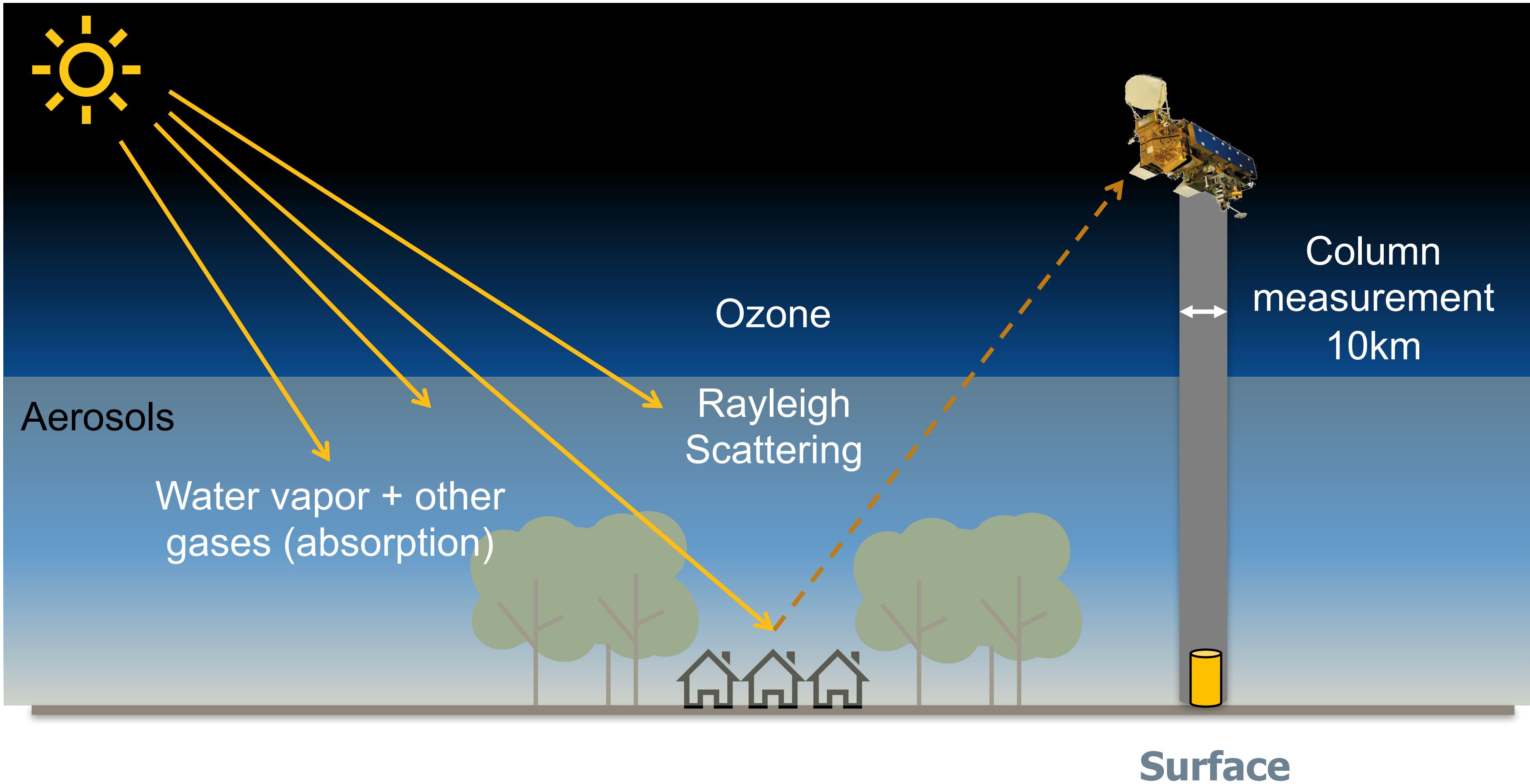


May 16, 2007

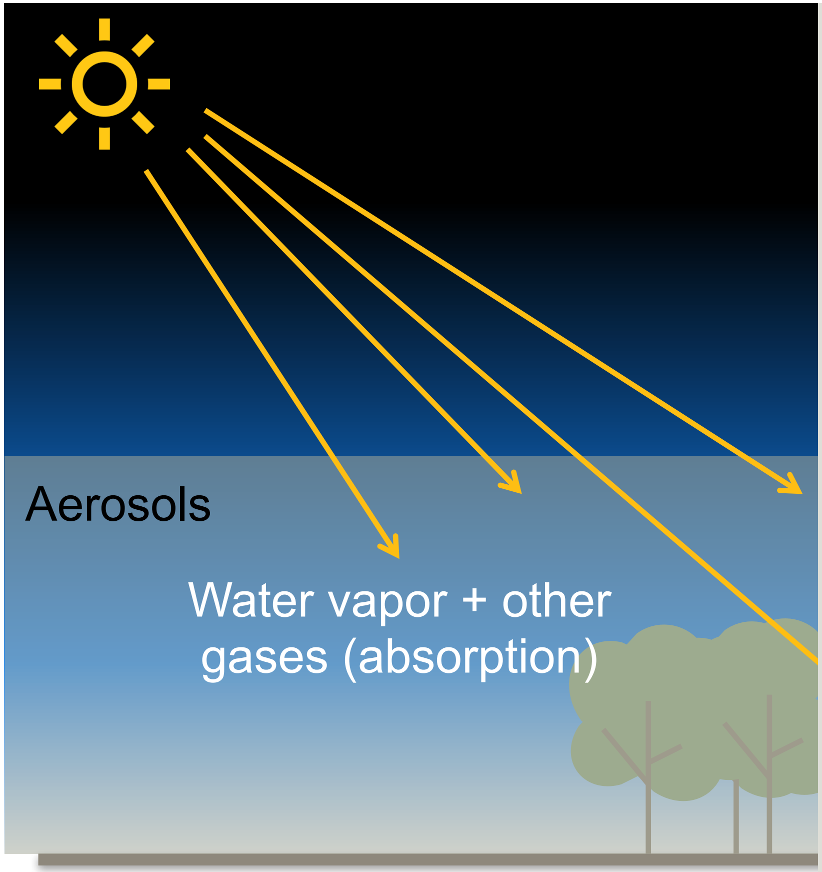



AOD (or AOT) to PM

What do satellites provide?



What do satellites provide?

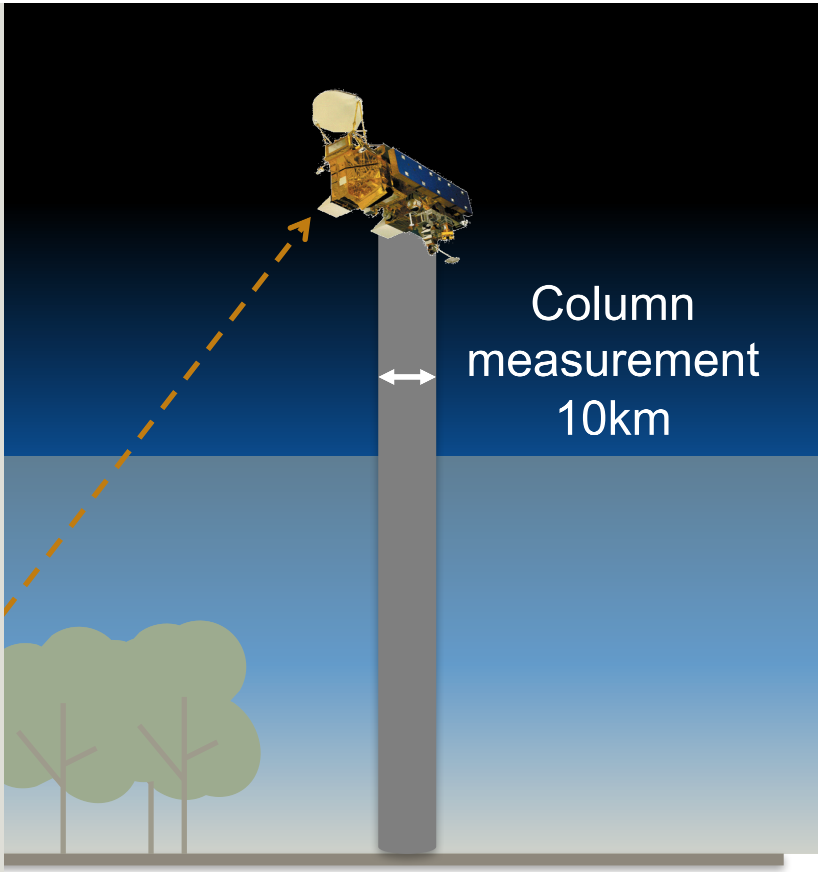


- AOT(τ)= $\int \beta_{ext}$ dz
  - particle size
  - composition
  - water update
  - vertical distribution

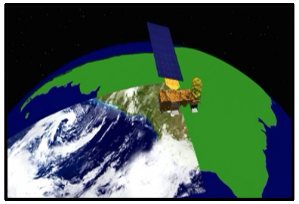
- There are satellite retrieval issues: inversion (e.g. aerosol model, background)

What do satellites provide?

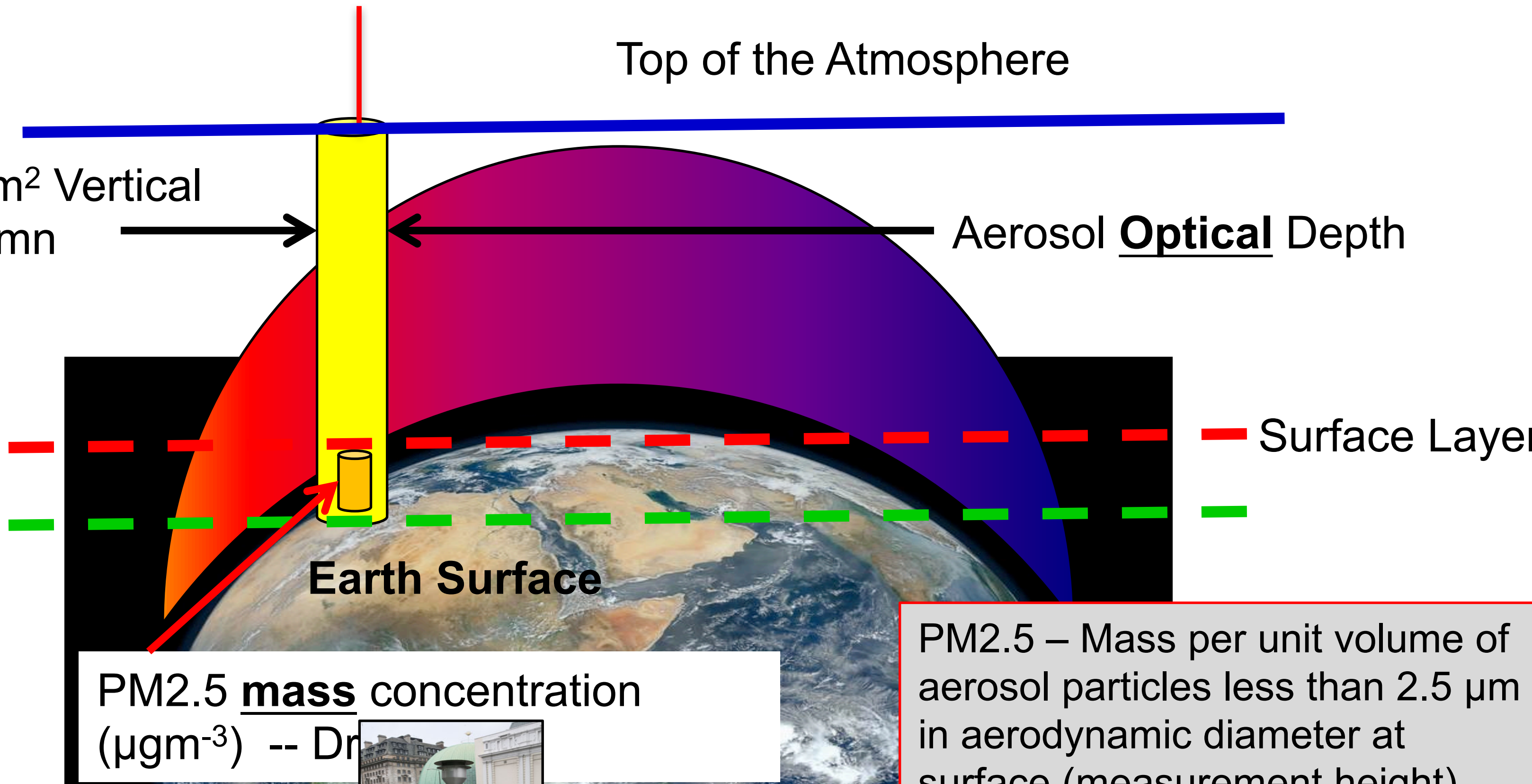
- Seven MODIS bands are utilized to derive aerosol properties
  - **0.47 µm**
  - 0.55 µm
  - **0.65 µm**
  - 0.86 µm
  - 1.24 µm
  - 1.64 µm
  - **2.13 µm**
- 10x10 km^2 resolution



Satellite vs Ground Observation



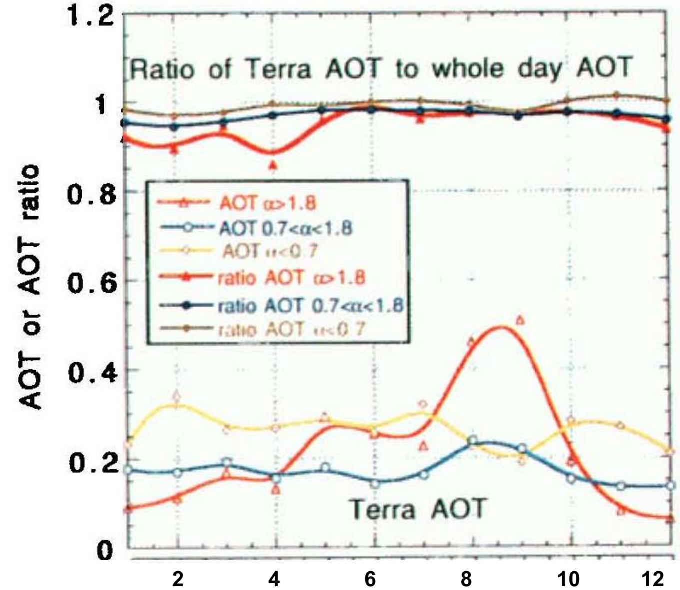
AOD – Column integrated value (top of the atmosphere to surface) - Optical measurement of aerosol loading – unitless. AOD is function of shape, size, type and number concentration of aerosols

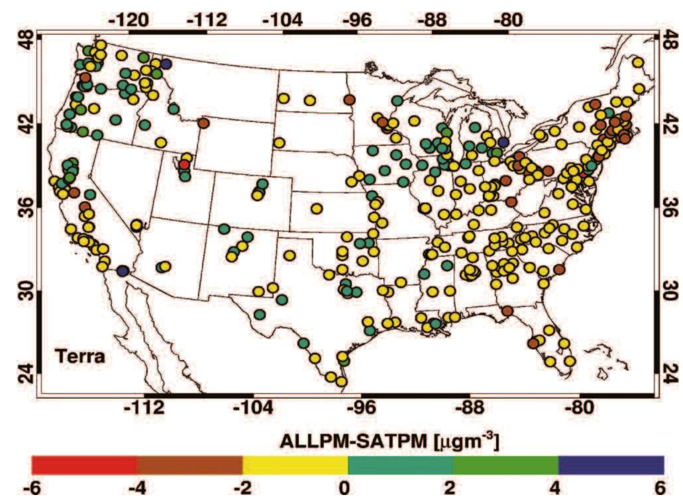


PM2.5 – Mass per unit volume of aerosol particles less than 2.5 µm in aerodynamic diameter at surface (measurement height) level

Support for AOD-PM2.5 Linkage

- Current satellite AOD is sensitive to PM2.5
  - Kahn et al. 1998
- Polar-orbing satellites can represent at least daytime average aerosol loadings
  - Kaufman et al. 2000
- Missing data due to cloud cover appear random in general
  - Christopher and Gupta 2010





AOD – PM Relationship

$$\text{AOD}(\lambda) = \int_{0\ \text{surface}}^{\text{top-of-atmosphere}} \beta_{ext,\,\rho}(\lambda, z)\, dz$$

$$C = \frac{4\rho r_e}{3Q} \times \frac{f_{PBL}}{H_{PBL}} \times \text{AOD}$$

- ρ: particle density
- Q: extinction coefficient

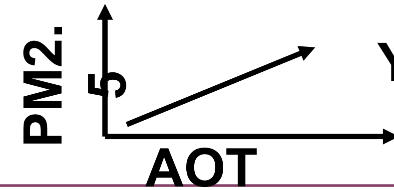
$\rbrack$ Compositio
n

- r_e: effective radius
- f_{PBL}: % AOD in PBL → Size distribution
- H_{PBL}: mixing height → Vertical Profile

PM2.5 Estimation: Popular Methods

Difficulty Level

Two Variable Method

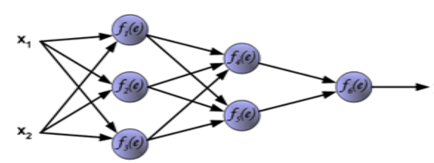


$Y = mX + c$

Multivariable Method

$$PM2.5 = \beta_0 + \alpha \times \tau + \sum_{n=1}^{m} (\beta_n \times M_n)$$

Artificial Intelligence



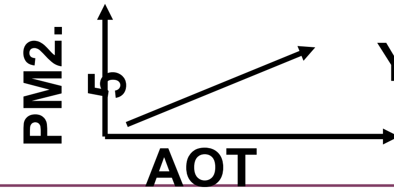
MSC

$$\text{Estimated } PM_{2.5} = \frac{\text{Model surface aerosol concentration}}{\text{Model AOD}} \times \text{Retrieved AOD}$$

PM2.5 Estimation: Popular Methods

Difficulty Level

Two Variable Method



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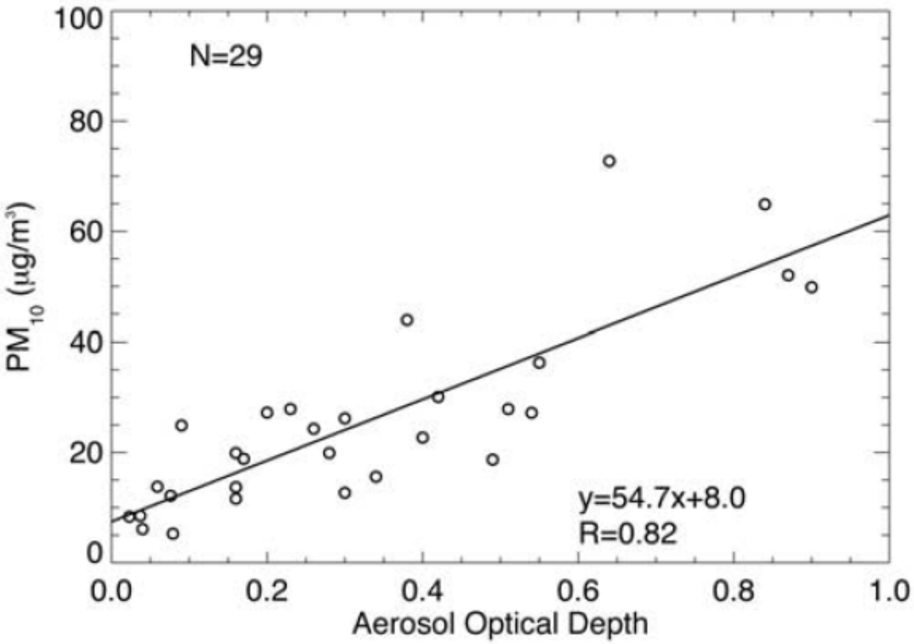
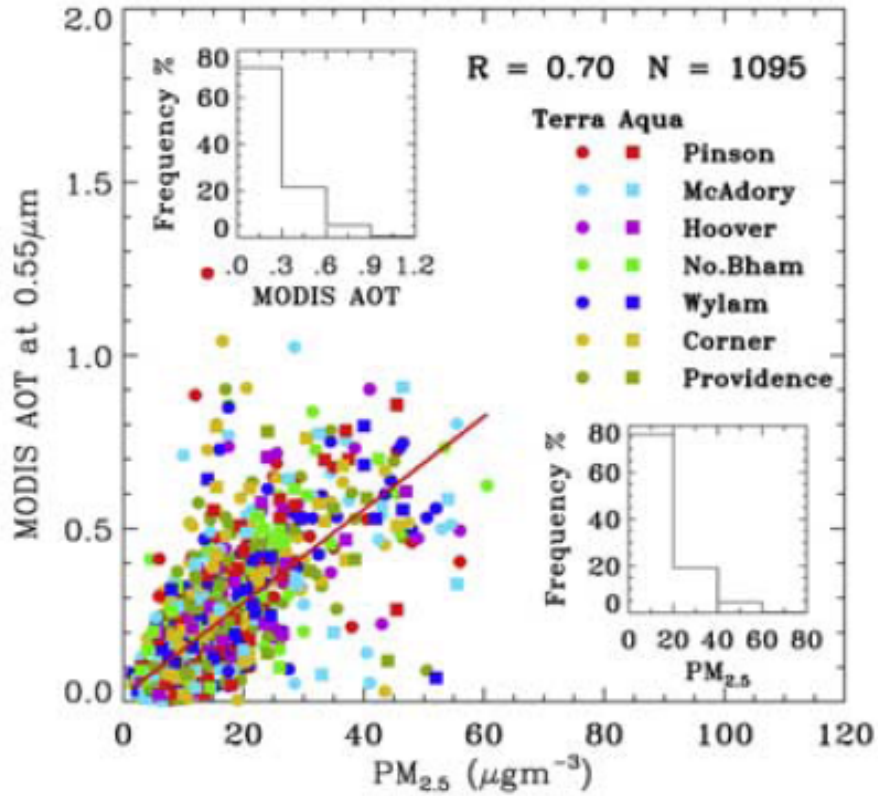
Simple Models from Early Days

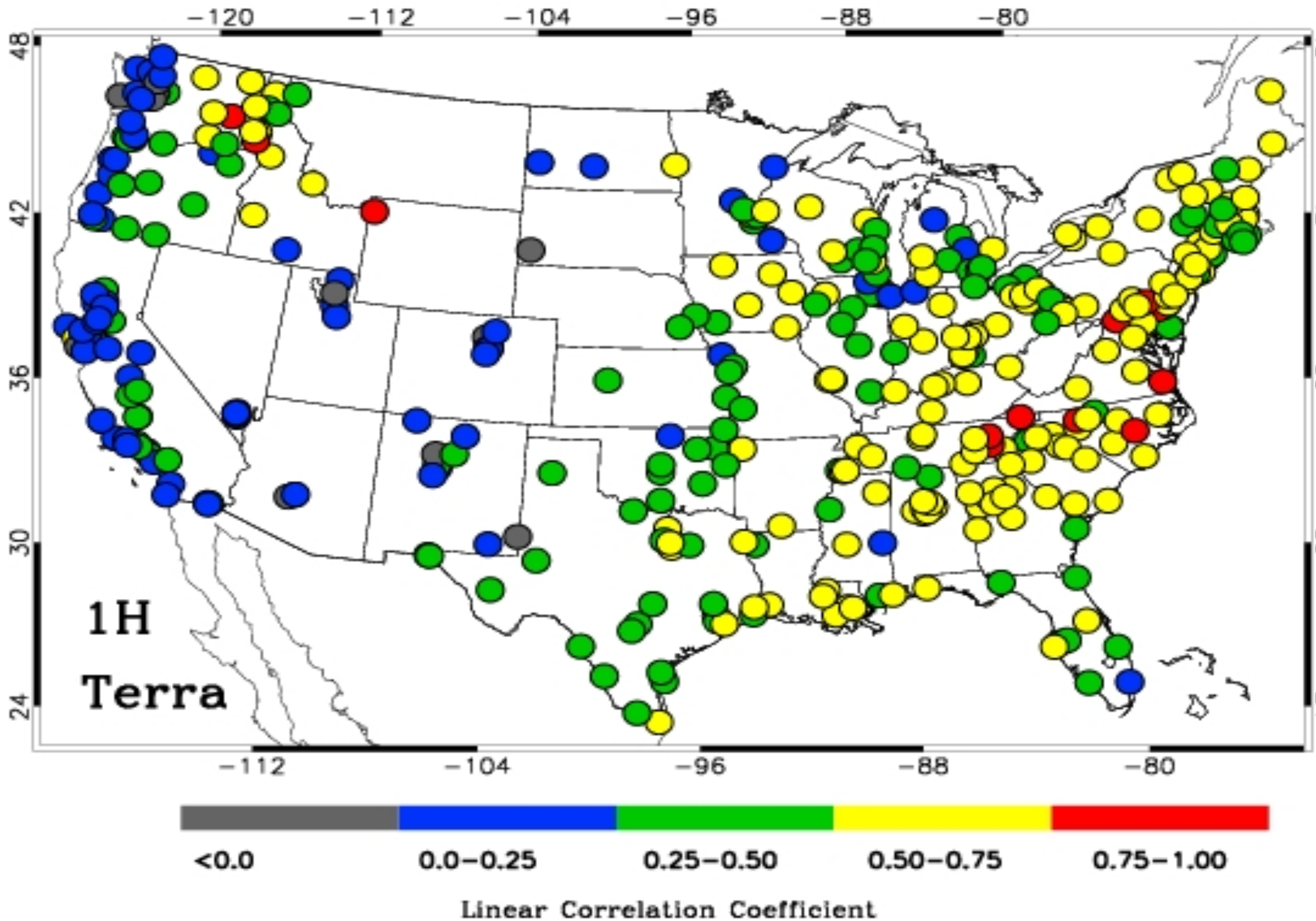


Source: Chu et al., 2003



Source: Wang et al., 2003

AOD-PM2.5 Relationship



Source: Gupta, 2008

PM2.5 Estimation: Popular Methods

Difficulty Level

Two Variable Method

$Y=mX + c$

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$$PM2.5 = \beta_0 + \alpha \times \tau + \sum_{n=1}^{m} (\beta_n \times M_n)$$

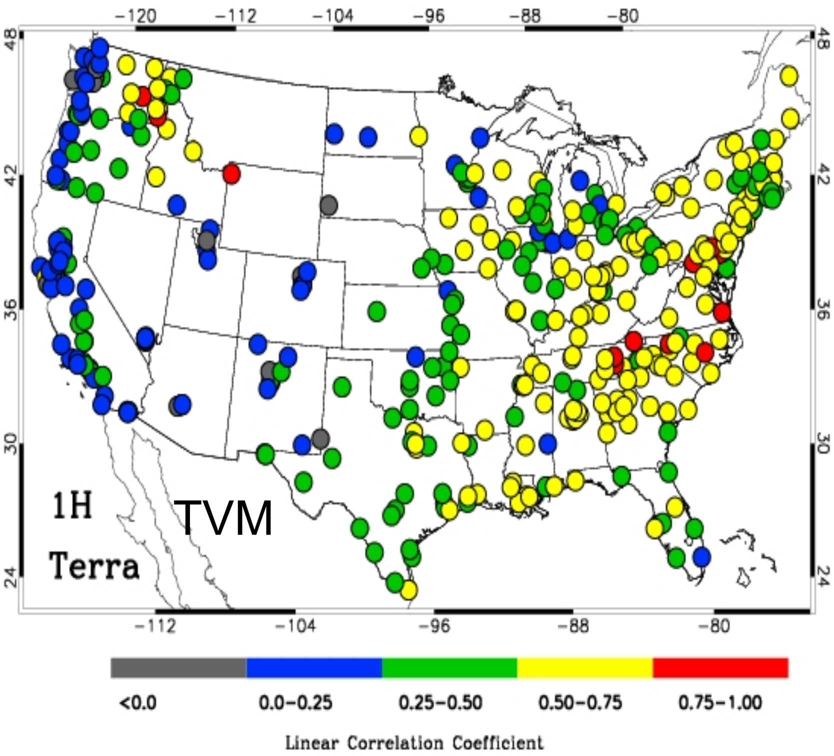
Artificial Intelligence

MSC

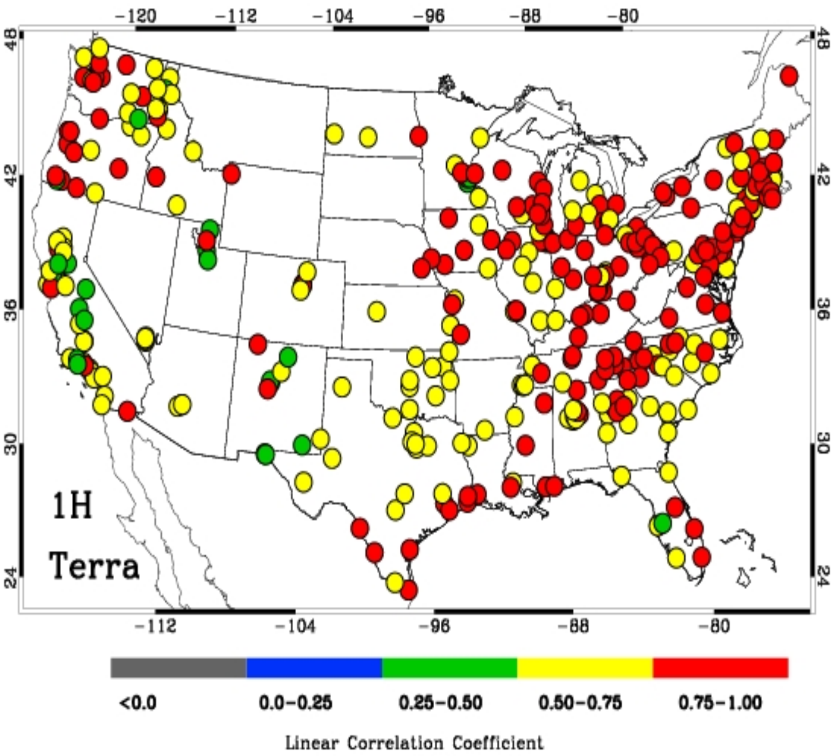
$$Estimated\ PM_{2.5} = \frac{Model\ surface\ aerosol\ concentration}{Model\ AOD} \times Retrieved\ AOD$$

Multi-Variable Method

Predictor: AOD



Predictor: AOD + Meteorology



Linear correlation coefficient between observed and estimated PM2.5

Source: Gupta, 2008

PM2.5 Estimation: Popular Methods

Difficulty Level

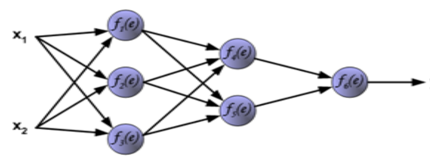
Two Variable Method

$Y = mX + c$

Multivariable Method

$$PM2.5 = \beta_0 + \alpha \times \tau + \sum_{n=1}^{m} (\beta_n \times M_n)$$

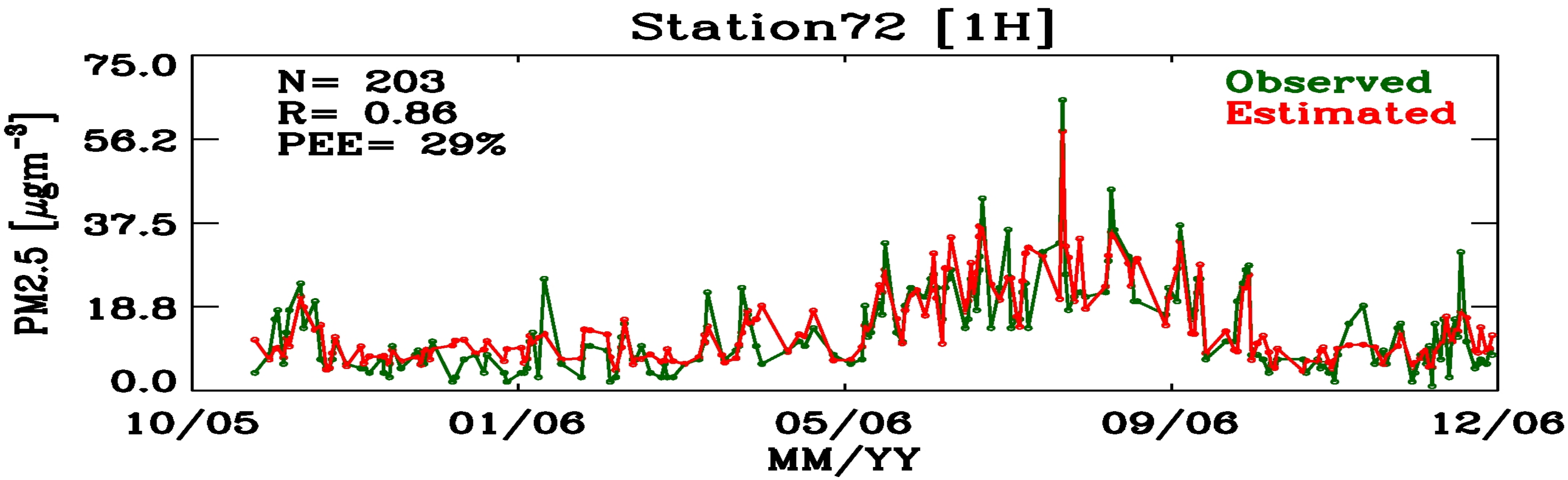
Artificial Intelligence

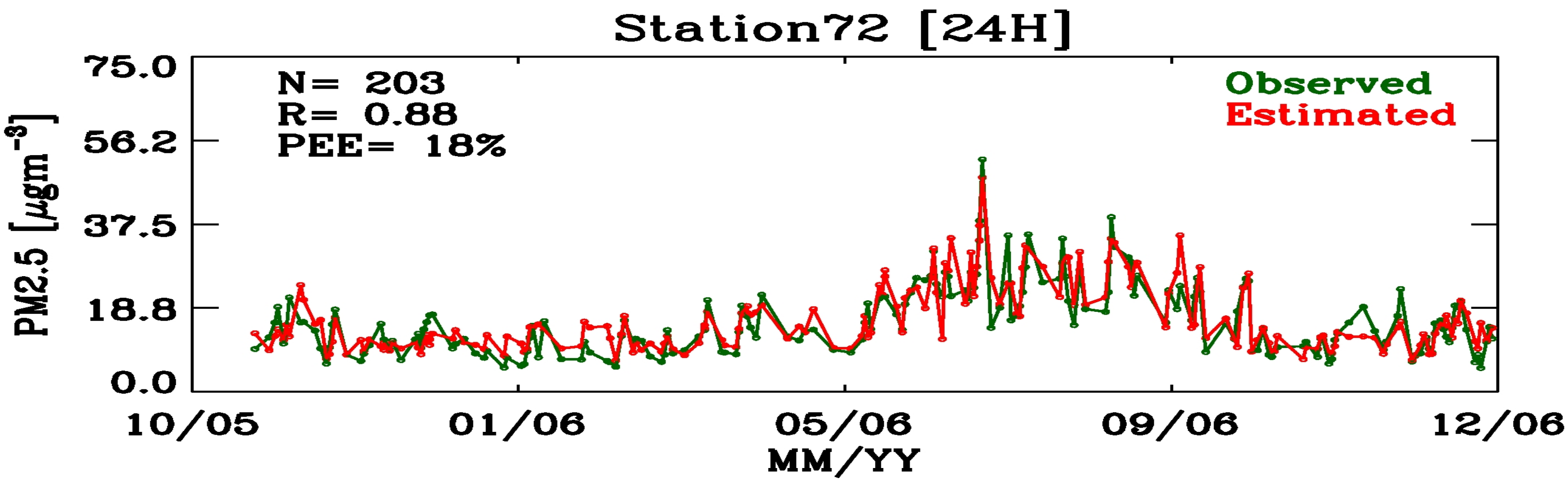


MSC

$$Estimated\ PM_{2.5} = \frac{Model\ surface\ aerosol\ concentration}{Model\ AOD} \times Retrieved\ AOD$$

Time Series Examples of Results from ANN

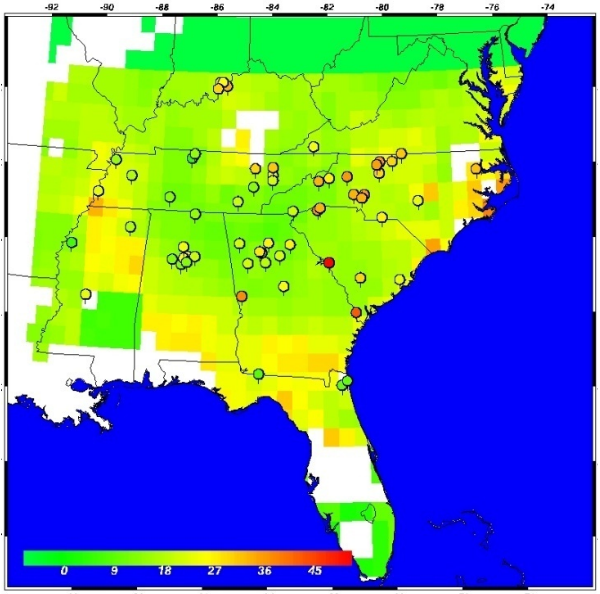




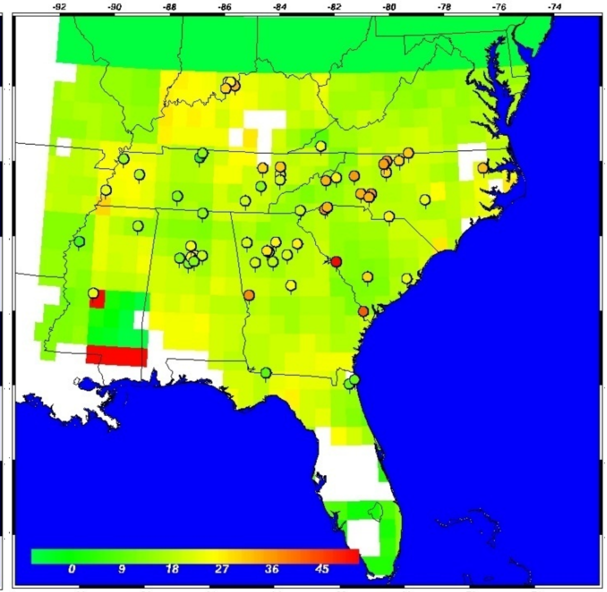
Source: Gupta, 2009

TVM vs. MVM vs. Artificial Intelligence

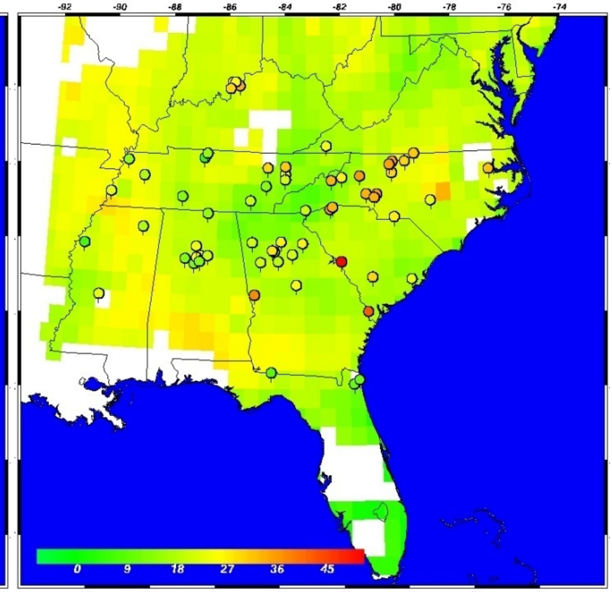
TVM



MVM



ANN



Source: Gupta, 2009

PM2.5 Estimation: Popular Methods

Difficulty Level

Two Variable Method

$$Y = mX + c$$

Multivariable Method

$$PM2.5 = \beta_0 + \alpha \times \tau + \sum_{n=1}^{m} (\beta_n \times M_n)$$

Artificial Intelligence

MSC

$$Estimated\ PM_{2.5} = \frac{Model\ surface\ aerosol\ concentration}{Model\ AOD} \times Retrieved\ AOD$$

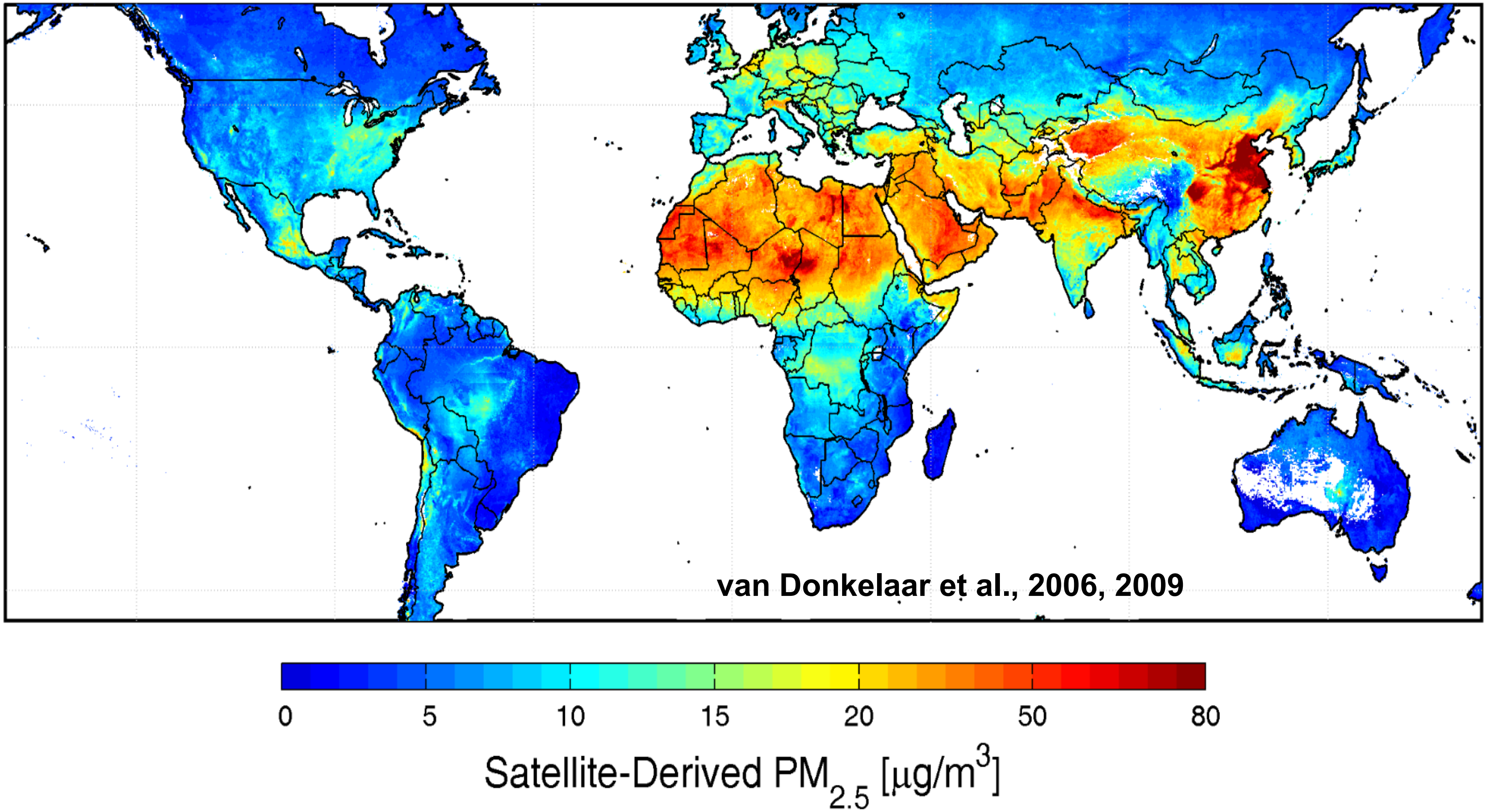
Scaling Approach

- Basic idea:
  - Let an atmospheric chemistry model decide the conversion from AOD to PM2.5
  - Satellite AOD is used to calibrate the absolute value of the model-generated conversion ratio

- Satellite-derived PM2.5 = $\left(\frac{\text{PM2.5}}{\text{AOD}}\right)_{\text{Model}} \times$ satellite AOD

Source: Liu et al., 2006

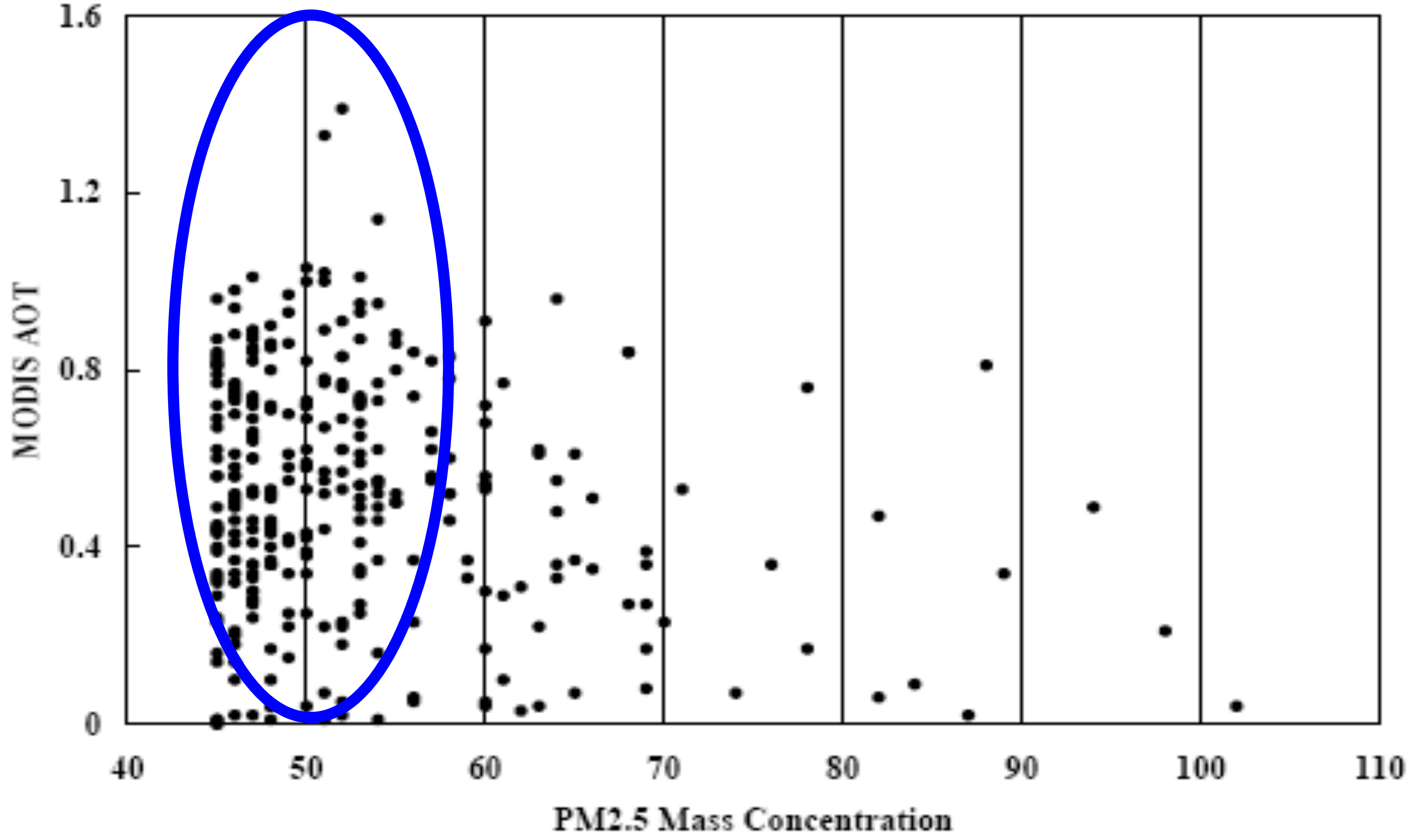
Annual Mean PM2.5 from Satellite Observations



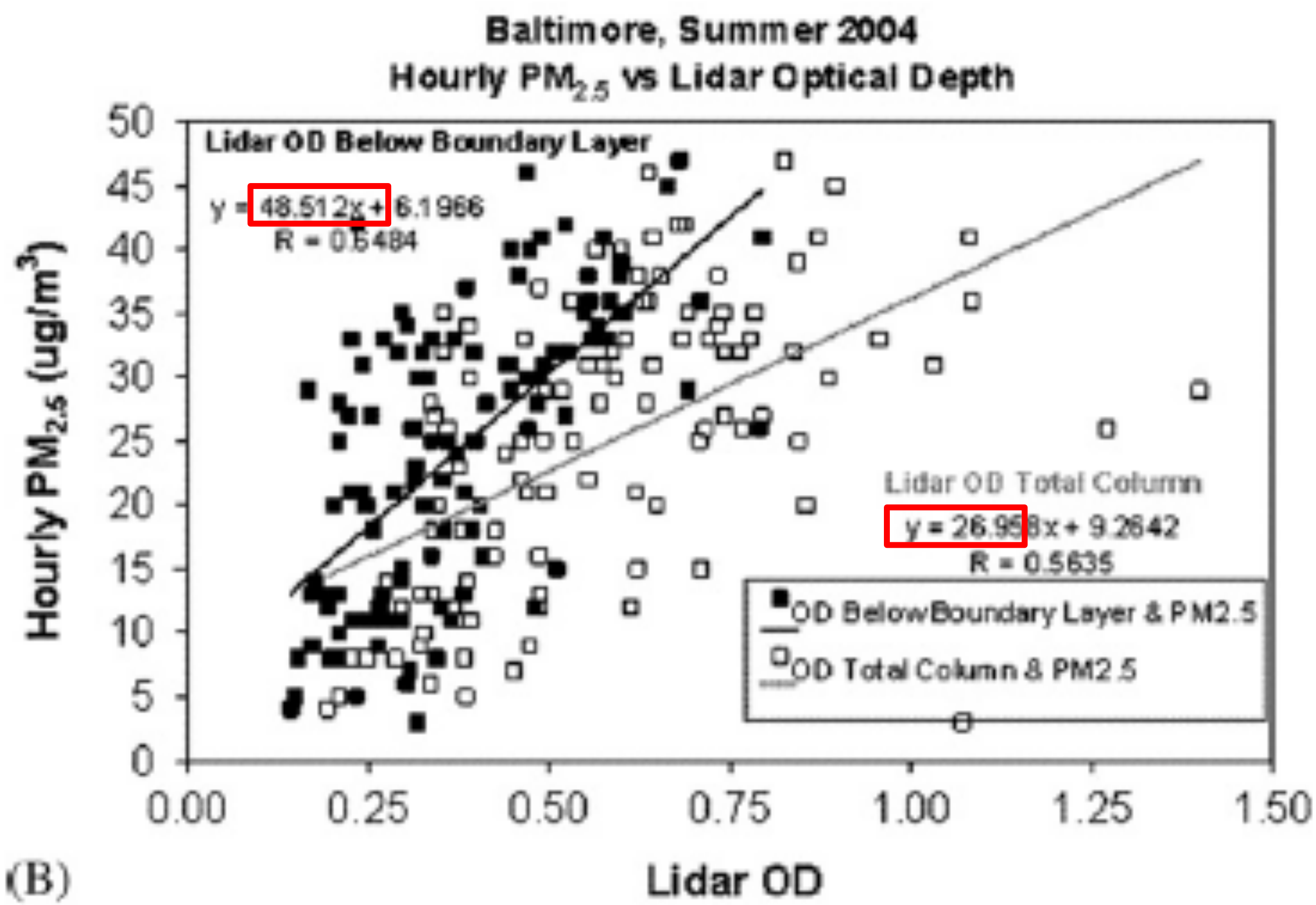
Questions to Ask: Issues

- How accurate are these estimates?
- Is the PM2.5-AOD relationship always linear?
- How does AOD retrieval uncertainty affect estimation of air quality?
- Does this relationship change in space and time?
- Does this relationship change with aerosol type?
- How does meteorology drive this relationship?
- How does the vertical distribution of aerosols in the atmosphere affect these estimates?

Limitation: Vertical Distribution of Aerosols



Vertical Distribution: Impact on AOD-PM2.5

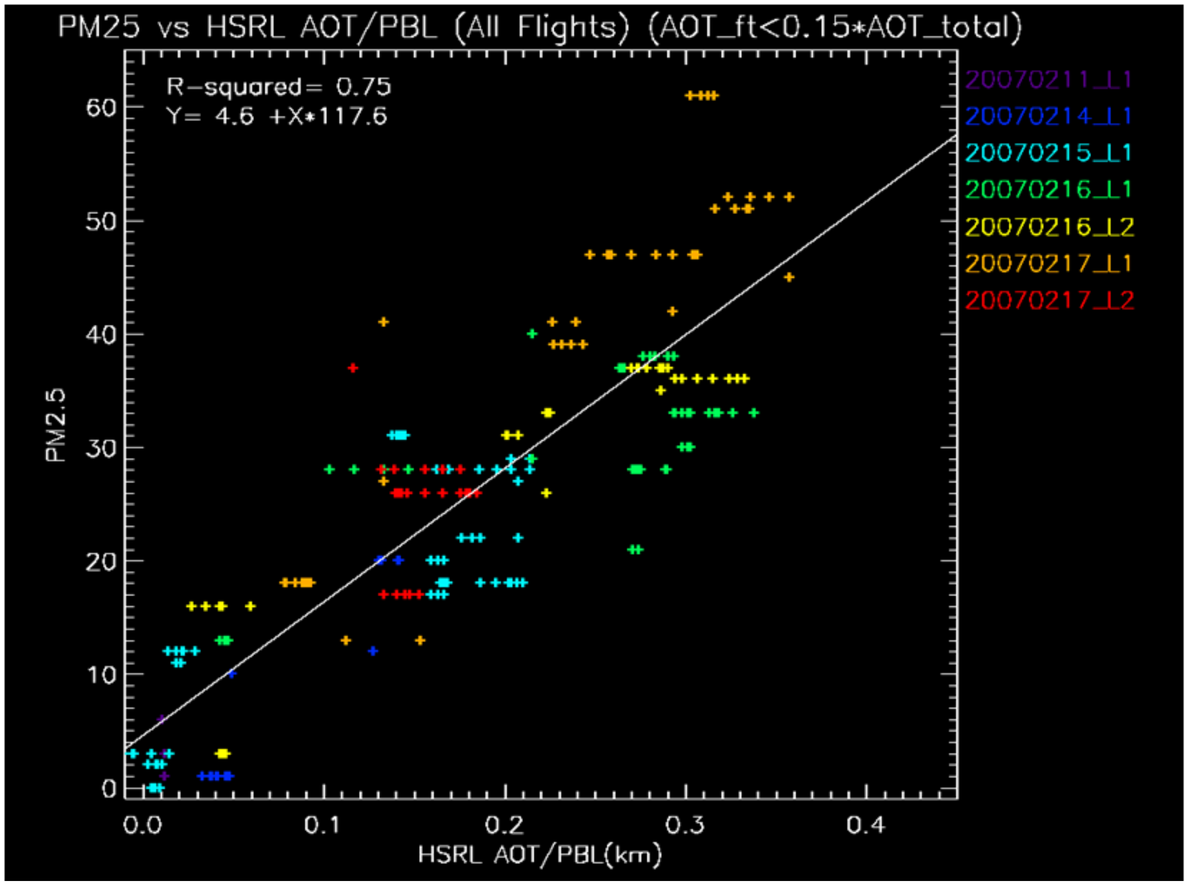


Source: Engel-Cox et al., 2006

Vertical Distribution: Impact on AOD-PM2.5

Correlation of Surface PM2.5 with HSRL AOD / PBL, All Flights

- Normalizing AOD with boundary layer height significantly improves correlation with $PM_{2.5}$ (R^2 increases from 0.36 to 0.75)
- With accurate estimates of PBL height, AOD can be good proxy for $PM_{2.5}$



Source: Al-Saadi et al., 2008

Assumption for Quantitative Analysis

When most particles are concentrated and well mixed in the boundary layer, satellite AOD contains a strong signal of ground-level particle concentrations

No textbook solution

Use of Satellite Data

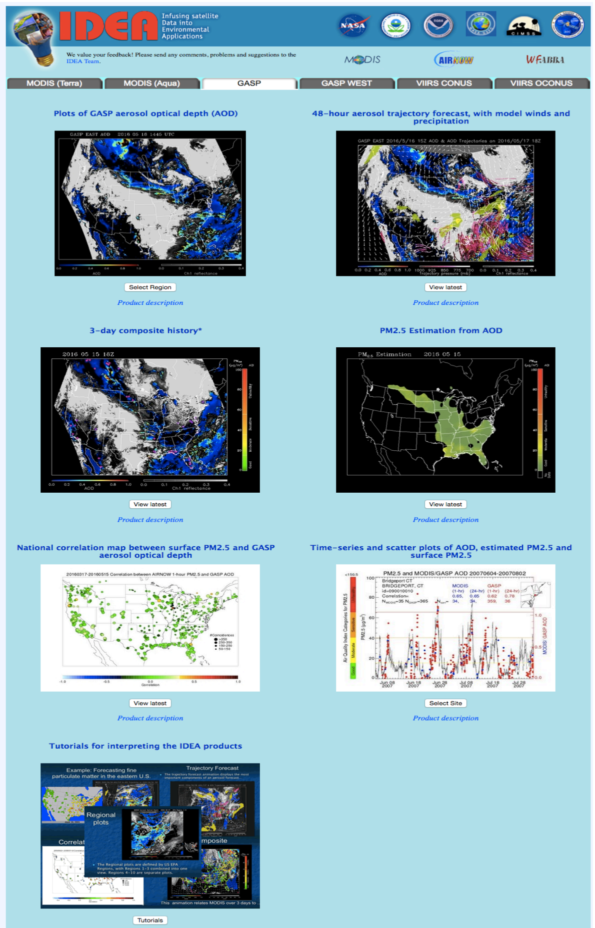
- Currently for research
  - Spatial trends of PM2.5 on regional to national level
  - Variability of PM2.5 between years
  - Model calibration/validation
  - Exposure assessment for health effect studies

- Near-future research
  - Spatial trends at urban scale
  - Improved coverage and accuracy
  - Fused statistical-deterministic models

- For Regulation?

How Satellite Aerosol Data is Being Used

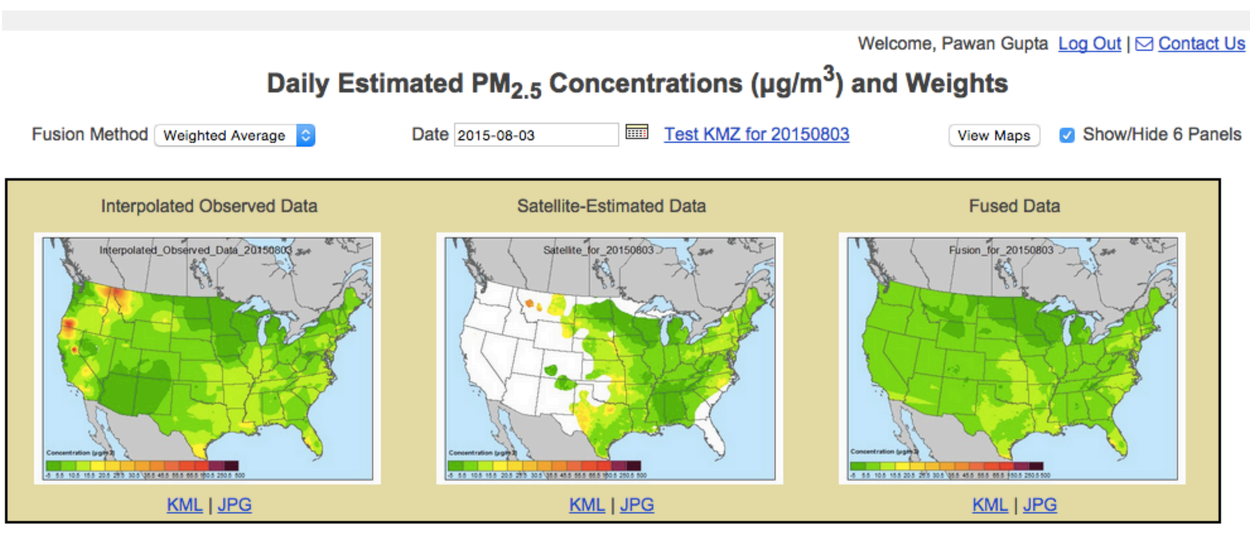
Infusing Satellite Data Into Environmental Applications



Objective: Near real-time product for state and local air quality forecasters

Goal: Improve accuracy of next day PM2.5 AQI forecasts during large aerosol events

AirNow Satellite Data Processor (ASDP)



Suggested Reading

2009 CRITICAL REVIEW

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DOI:10.3155/1047-3289.59.6.645
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R.M. Hoff

Remote Sensing of Partic
from Space: Have We Rea
Promised Land?

dard Earth Sciences

y of

IMPLICATIONS

Satellite measurements are going to be an integral part of the Global Earth Observing System of Systems. Satellite measurements by themselves have a role in air quality studies but cannot stand alone as an observing system. Data assimilation of satellite and ground-based measurements into forecast models has synergy that aids all of these air quality tools.

The use of the AOD as a measure for mass concentration has skill in some regions but less in others and does not provide a uniform way to measure aerosols across the United States. We discussed in Table 4 the range of mea-

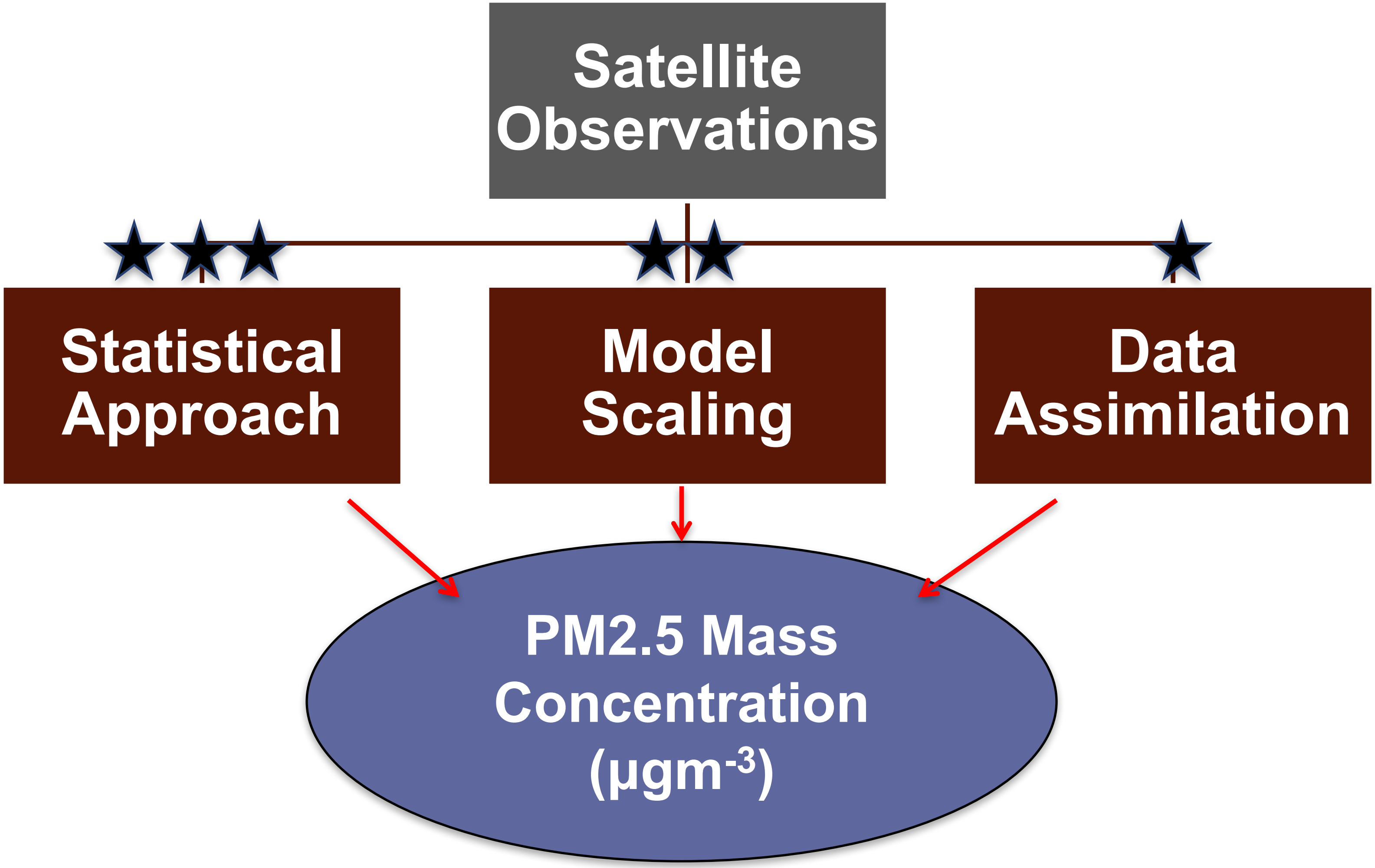
dards (NAAQS).[142] The 39-yr history of those standards parallels the time period that satellite meteorology and observations have developed and yet, to date, no satellite measurements have been used to quantitatively address the NAAQS. From the review conducted here, only one congres-

EPA has taken a satellite observations role for itself in the Exceptional Events Rule.[144] If a region can show conclusively that they are being impacted by an event (a fire, a dust storm, etc.) that is outside of their jurisdiction to regulate, the event can be flagged as a nonexceedance event. This provides a significant motivation for regional

ellite data possible in significant exceedances only. Applications such as event identification, transport, and atmospheric composition determination are strengths of satellite measurements. Where high precision is required (compliance monitoring, the "but for" test, and quantitative measurement of visibility effects on Class I areas), satellite data are presently of limited utility.

Although the desire for the use of satellite data for air quality purposes is widely stated, the reality is that many of the measurements have not yet met the promise that they can be operationally used for today's air quality monitoring requirements. Precision in measuring AOD is

Satellite Remote Sensing of PM2.5 - Summary



Questions and Discussion

- What are three differences between AOD and PM2.5 mass concentration ?

- List three advantages of using satellite observations for PM2.5 air quality monitoring

- What are the pros and cons of using scaling approach over regression method ?

Suggested References

- Al-Saadi, J., Szykman, J., Pierce, R. B., Kittaka, C., Neil, D., Chu, D. A., Remer, L., Gumley, L., Prins, E., Weinstock, L., Macdonald, C., Wayland, R., Dimmick, F., Fishman, J., Improving national air quality forecasts with satellite aerosol observations, *Bull. Am. Meteorol. Soc.*, *86*(9), 1249–1264, 2005.
- Gupta, P., Christopher, S. A., Wang, J., Gehrig, R., Lee, Y.C., Kumar, N., Satellite remote sensing of particulate matter and air quality over global cities, *Atmos. Environ.*, *40* (30), 5880-5892, 2006.
- Gupta, P., and S. A. Christopher, An evaluation of Terra-MODIS sampling for monthly and annual particulate matter air quality assessment over the southeastern United States, *Atmospheric Environment 42,* 6465-6471, 2008b.
- Liu, Y., J. A. Sarnat, V. Kilaru, D. J. Jacob, and P. Koutrakis, Estimating ground level pm2.5 in the eastern united states using satellite remote sensing, *Environmental Science & Technology*, *39*(9), 3269-3278, 2005.
- Wang, J., and S. A. Christopher, Intercomparison between satellite-derived aerosol optical thickness and $PM_{2.5}$ mass: Implications for air quality studies, *Geophys. Res. Lett.*, *30*(21), 2095, doi:10.1029/2003GL018174, 2003.
- van Donkelaar, A., R. Martin V., Park R. J., Estimating ground-level $PM_{2.5}$ using aerosol optical depth determined from satellite remote sensing. *J. Geophys. Res., 111,* D21201, doi:10.1029/2005JD006996, 2006.
- van Donkelaar, A., R. V. Martin, M. Brauer and B. L. Boys, Use of Satellite Observations for Long-Term Exposure Assessment of Global Concentrations of Fine Particulate Matter, Environmental Health Perspectives, 123, 135-143, do:10.1289/ehp.1408646, 2015.

Tour to IDEA

Accessing near real time satellite data for US air quality

- Air Quality Case Study
  - Fires in Canada and Smoke Transport over US, June 09, 2015
  - Buffalo fires, Wyoming, August 13, 2016

- Tools
  - IDEA - http://www.star.nesdis.noaa.gov/smcd/spb/aq/
  - eIDEA - http://www.star.nesdis.noaa.gov/smcd/spb/aq/eidea/

Questions